Decentralized Multiaccess MAC Protocol for Ad-Hoc Networks

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Abstract— **In ad-hoc radio networks, mechanisms on how to access the radio channel are extremely important in order to improve network efficiency and, when needed, to guarantee QoS. Traditionally, Medium Access Control (MAC) protocols in ad hoc networks have been designed to face off the well known collision resolution problem. However, when using advanced signal processing techniques, general assumptions on collisions and packet loss are no longer valid. Besides, little has been reported about MAC algorithms dealing with multiaccess channels in ad hoc networks. In this paper, we present a novel decentralized multiaccess MAC protocol for Ad Hoc networks. This MAC protocol is an hybrid CDMA-TDMA in which a cross layer approach has been followed to dinamically adapt to the traffic load. Closed expressions for the throughput and delay of the network are presented as a function of the multipacket reception capability of the receiver, the number of codes and the packet retransmission probability.**

I. Introduction

In ad-hoc radio networks, mechanisms on how to access the radio channel are extremely important in order to improve network efficiency and, when needed, to guarantee QoS. Traditionally, these mechanisms are relegated to the Medium Access Control (MAC) sub-layer of the data link layer. However, interaction with other layers can be of interest in order to cope with ad hoc network harsh conditions.

A conventional assumption on the reception capability at the physical layer (PHY) is commonly considered in the most widely MAC techniques used nowadays. That is, consider that when two or more packets are transmitted simultaneously a collision occurs and consequently, the information is lost. To recover the information, the colliding packets have to be retransmitted. In order to face-off the collision resolution problem, the design of decentralised MAC in ad-hoc networks is usually based on random access mechanisms and/or RTS-CTS handshake [1], [2], [3]. Clearly, the collision resolution efficiency of these techniques will mainly depend on the traffic load of the network. Hence, the optimal MAC procedure would be similar to the one presented in [4] able to evolve, according to an increase of the traffic load, from a contention to a non-contention mode in a decentralized fashion.

On the other hand, many current signal processing techniques introduce Multi Packet Reception (MPR) capability at PHY layer by means of spatial or code diversity, the main consequence of this MPR capability is the possibility to allow a multiaccess communication channel. The improvement in throughput performance when spatial or code diversity is introduced is demonstrated in [5],[6]. However, non of them consider a cross-layer approach, i.e., the MAC mechanisms applied are still working under the conventional assumption of collision and hence, without any knowledge about the physical layer. This loose of cross-layer interaction leads to a suboptimal performance of the system. The idea of cross-layer is based on the interaction between layers in order to improve and reach an optimal system performance [7],[8].

Recently, some articles in the literature refer to the physical layer packet reception capability by using the so called MPR matrix and use this MPR matrix in the development of MAC procedures [9],[10],[11]. Each element of this matrix, $C_{k,n}$ is the probability of successfully receive k packets when n packets have been sent. Basically, assuming some statistical independency between both packets and users, these probabilities can be obtained from the bit error rate (BER) and binomial distributions. The work in [9] is perhaps the first to introduce the concept of MPR matrix where modifications of the retransmission probability of the Aloha protocol were presented. Additionally, little has been reported for ad hoc multiaccess systems where nodes can transmit directly to each other and any node is a potential receiver or transmitter [11].

In this article, we present a novel multiaccess decentralized MAC protocol for ad-hoc networks that is an hybrid CDMA-TDMA specially designed to dinamically adapt from a contention to a non-contention mode according to the traffic load and to fully exploit the MPR capabilities of the receiver. In our system, time and code resources are controlled by means of two degrees of freedom, the retransmission packet probability Pr and the number of codes Nc to be allocated to a particular node. By adjusting these two variables depending mainly on the traffic load and the architecture of the receiver, we aim throughput and delay improvement and give expressions for this performance evaluation. We note that cross-layer interaction is used in order to improve and reach an optimal system performance.

The remainder of this paper is structured as follows. Section II presents the system model. In section III, the system is analyzed following a Markov chain approach and an expression that relate network packet reception performance with the receiver multipacket capability is presented. In section IV, closed expressions of both throughput and delay of the network are presented as a function of the retransmission probability P_r and the number of codes Nc. And finally, conclusions are presented in section V.

II. System Model

We consider single-hop (fully connected) packet oriented CDMA-TDMA ad-hoc network in which all nodes are identical and share the same common channel. The spreading codes are supposed to be known by all the nodes in the network. Each node can be either transmitter or receiver but not both at the same time, i.e., half duplex communication is assumed. Synchronization and association procedures could be similar to the ones in [3] and are not tackled here. Hence, it is assumed that every node is perfectly synchronized and knows the number of nodes present in the network.

The network is characterized by both, the number of users M in the network and the number of codes N to be used in this network (usually $M \geq N$). Time is slotted and each time slot is assigned to one node. The duration of a slot is the time needed for the transmission of a data packet. During one time slot, the node owning that slot, i.e., the node to whom that slot has been assigned, have N_c codes ($Nc \leq N$) to transmit its packets simultaneously. Meanwhile, the remaining $M-1$ nodes contend for the residual codes Nr ($Nr = N - Nc$). The node owning the slot is called multiple node and the nodes contending for the codes are called simple nodes. The multiple node can send at most Nc packets through Nc different codes simultaneously (one packet per code). On the other hand, simple nodes can contend for sending one packet at the most. Besides, during the contention, a simple node with a packet waiting for retransmission, also called backlogged simple node, retransmits its packet with probability equal to Pr through a code chosen randomly from the Nr codes. If on the contrary, a simple node has a packet to be transmitted for the first time, i.e., is an unbacklogged simple node, the packet is transmitted with probability equal to one and again, through a code chosen randomly from the Nr codes. As the multiple node is changing in a slot by slot basis, a node becomes a multiple node once every M slots having the possibility to send at most Nr packets.

The main idea behind this MAC is to present a novel strategy on decentralized resource management for ad hoc networks. An hybrid CDMA-TDMA system is considered where the MAC protocol dynamically evolves from an allocation (or non-contention) protocol at high traffic loads to a contention slotted Aloha protocol at low traffic loads. This evolution is done by properly adjusting the number of codes Nc and the retransmission probability Pr in order to optimize network performance. Notice that the fact of allocating codes in a decentralized fashion is, to the best of our knowledge, a totally new approach in ad hoc networks. We will see, that not only the traffic load but also the information about the colliding codes (codes used by more than one node)[1] will be used together with the receiver MPR matrix (or equivalently the BER associated to a specific reception architecture) as information agents for MAC optimization.

By adjusting Pr, the time resource is controlled, i.e., contention is regulated by increasing retransmission probability at low traffic and reducing it at high traffic. On the other hand, by adjusting Nc, the code resource is managed, i.e., a high number of codes is assigned to the multiple node at high traffic and low number of codes are allocated at low traffic. Both the BER and the information about the collided codes are used to evaluate the multipacket reception capability of the receiver.

The multipacket reception performance of the receiver is modelled by the receiver MPR matrix. However, to properly model the MPR capability of the network in ad-hoc networks many considerations have to be taken into account. First, since transceivers are half-duplex, a node in transmission mode cannot successfully receive packets and second, a node can successfully demodulate a packet not intended for that node. In this two situations packets are lost. Furthermore, in our system nodes choose codes randomly and hence, in the event of two or more nodes using the same code, packets are lost due to collision. Since the detection of active users in multiuser detectors is not new [12], [13], we will assume that the receiver is a Multi User Detector (MUD) which includes a first stage where collided codes (or codes used by more than one node) are detected and consequently, are discarded in demodulation.

Figure 1 presents an example of a system with eight nodes. The length of the frame depends on the number of nodes, in that example, the frame is 8 time slots long. In slot 1, the multiple node is the node 1 and uses 2 codes ($Nc = 2$) to send packets to nodes 4 and 5 (codes are indicated by means of arrows of different grey shade). Nodes 2 and 8 also transmit a packet to nodes 7 and 3 respectively. However, nodes 2 and 8 randomly choose the same code and hence, packets collide and are lost. Besides, node 6 sends a packet to node 1, although this packet do not collide, it is also lost because node 1 is in transmission mode. In that situation, assuming that nodes can detect and discard collided packets (in this case packets from nodes 2 and 8) and considering a fully connected network, nodes 5 and 4 would receive 3 packets to demodulate (packets from node 1 and 6), but only 1 among these 3 is intended for each of them. Success in transmission would depend on the MPR capabilities of the receivers. In the following slot, the general behavior of the network would be similar as the one stated here. However, in slot 2, the multiple node would be node 2 and node 1 would become a simple node. Notice that each node becomes a multiple node once every eight slots.

III. System Analysis

Before we proceed to the analysis of the system, it is important to state the following assumptions:

1. Nodes generate packets according to independent Poisson processes with equal arrival rate ($\lambda\ packets/slot$).
2. Perfect feedback information about the status of transmission is received instantaneously by each node.
3. All nodes are assumed to have the same receiver architecture that can be modelled with a *receiver* MPR matrix

[1] In this paper, the word collision will be used to refer the fact that two or more nodes choose the same code for transmission

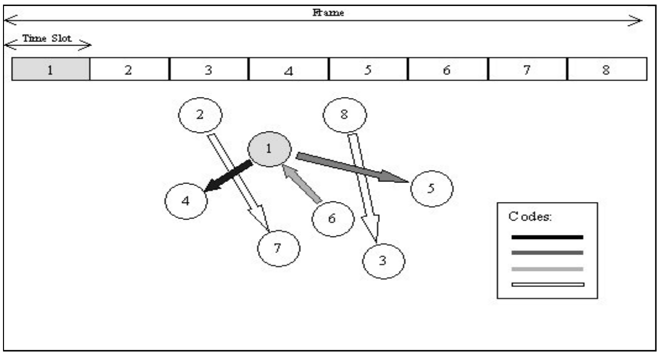

Fig. 1. Network example with 8 nodes and 4 codes

C as described in section I. (For more information on the MPR matrix, the reader is referred to [8])

4. Packets in a node have equal probability to be transmitted to any other node.

5a. From the time a simple node generates a packet until that packet is successfully received, the user is blocked in the sense that he can not generate (or accept form his input source) a new packet for transmission, i.e., a simple user can hold at most a packet at a time.

5b. The multiple node can hold at most Nc packets at a time.

Notice that assumptions from 1 to 5.a are considered standard assumptions [14],[15]. Particularly, for the sake of simplicity, assumption 5a has been traditionally used in the literature even though it does not exactly model a real system. With the introduction of 5b, assumption 5a is relaxed.

Our analysis is based on the Markov Chain approach proposed by Kleinrock and Lam [16] and followed afterwards by Bao and Tong [15]. Kleinrock and Lam model a finite population slotted Aloha system with the number of backlogged nodes n as the network state. Bao and Tong used the same model to compare the performance of a CDMA centralized system versus a CDMA ad-hoc system. Here, for a M node network, the Markov chain is a two dimensional $(N_c+1)\times M$ state chain which models both, the number of backlogged packets in the multiple node buffer which is in the range of $[0, N_c]$ and the number of simple nodes in backlogged state, i.e., that have a packet for retransmission which is in the range of $[0, M-1]$. For our analysis, we will consider that the multiple node do not change from slot to slot and is always the same node. However, considering that all nodes are identical and from a network point of view, this assumption is considered valid for the computation of the stationary probabilities of the Markov chain that models our system.

This Markov chain is characterized by a $((N_c+1)\times M)\times((N_c+1)\times M)$ transition matrix P in which each entry is $p_{(i,n),(j,k)}$ and denotes the probability of network state to go from state (i,n) to state (j,k) in one time slot. As it is fully described at the end of this section, transition from i to j models the evolution of the number of backlogged packets of the multiple node, whereas transition from n to k models the evolution of the number of backlogged simple nodes. Determining the Markov Chain transition matrix is not an easy task. The problem arises when in ad-hoc networks the receiver MPR matrix do not completely characterize the multipacket reception capability of the network, as it was mentioned in section II. Bao and Tong, [15], have done work on modifying the receiver MPR matrix to characterize the MPR capability of the network according to the properties of ad-hoc networks. However, this characterization is not enough in the problem stated here. The fact that the multiple node can transmit more than one packet at a time also affects the MPR capability of the network. We define the *network* MPR matrix $R^{(M_{ll})}$ as a function of the number of nodes M_{ll} that do not transmit in the current slot as follows:

$$R^{(M_{ll})}=\begin{pmatrix} r_{1,0}^{(M_{ll})} & r_{1,1}^{(M_{ll})} & 0 & \dots & \dots & 0 \\ \vdots & \vdots & \dots & \vdots & \vdots & \dots \\ \vdots & \vdots & \dots & \vdots & \vdots & \dots \\ r_{M,0}^{(M_{ll})} & r_{M,1}^{(M_{ll})} & \dots & \dots & \dots & r_{M,M}^{(M_{ll})} \end{pmatrix} \qquad (1)$$

In equation (1), $r_{Ln}^{(M_{ll})}$ is the probability that n out of L non-collided packets in the time slot are successfully received by their intended receivers in the network when M_{ll} nodes are in reception mode. Notice that when $M_{ll}=0$, $r_{Ln}^{(0)}=0$. The conversion of C (the *receiver* MPR matrix) to $R^{(M_{ll})}$ (*network* MPR matrix accounting for the ad hoc network properties) is provided by the following theorem:

Theorem 1: Under assumptions 1 to 5, given a total L non-collided packets are transmitted in a time slot and that M_{ll} ($\geq M-L$) nodes are in reception mode, the probability that there are $n\leq L$ successfully received packets by their intended receivers in the network is given by equation (2).

Where:

$$q_{L,l}=\binom{L}{l}\left(\frac{M_{ll}}{M-1}\right)^{l}\left(1-\frac{M_{ll}}{M-1}\right)^{L-l} \qquad (3)$$

$$d_{L,a_i,b_i}=\sum_{k=b_i}^{L-(a_i-b_i)}\frac{\binom{a_i}{b_i}\binom{L-a_i}{k-bi}}{\binom{L}{k}}\,c_{L,k} \qquad (4)$$

In (2), M_{ll} is used to account for nodes in reception mode in the current slot, $q_{L,l}$ is used to determine the probability that l among L non-collided packets reach their intended nodes due to half-duplex communication and d_{L,a_i,b_i} is used to determine the probability of successfully receive b_i packets when a_i packets are intended for that node. A proof of (2) is shown in [15] with the difference that whereas in [15] M_{ll} is fixed to $M-L$, in our system M_{ll} depends on whether the multiple node sends more than one packet or not. Notice that the fact that L accounts for non-collided packets implies both, that the first stage of the receiver successfully detects and discards colliding packets and that the probability of having L non-collided packets must be considered in the system analysis.

The transition from one state to another of the Markov chain is determined by two events, i) the difference between unsuccessful transmissions of unbacklogged packets and the

$$r_{Ln}^{(M_{ll})}=\sum_{l=n}^{L}\sum_{J=\min(l,1)}^{\min(l,M_{ll})} q_{L,l}\ \frac{\binom{M_{ll}}{J}}{(M_{ll})^{l}}\sum_{(\sum a_j)=l}\frac{l!}{a_1!\cdots a_J!}\Big(\sum_{(\sum b_j)=n}\Big(\prod_{i=1}^{J} d_{L,a_i,b_i}\Big)\Big) \tag{2}$$

successful retransmissions of backlogged packets of the multiple node and ii) the difference between the number of unsuccessful transmissions from unbacklogged simple nodes and the number of successful retransmissions from backlogged simple nodes. That can be seen as, for a given $p_{(i,n),(j,k)}$, transition from i to j depends on i) and transition from n to k depends on ii). Hence, following [15], $p_{(i,n),(j,k)}$ can be obtained by means of (5):

$$p_{(i,n)(j,k)}= \tag{5}$$
$$\begin{cases} \sum\limits_{z=0}^{N_c-i}\sum\limits_{y=n-k}^{n}\sum\limits_{x=0}^{M-n-1} S(x,y,z)Q_{z,x,y} & \text{for } \begin{cases} 0\le k<n \\ 0\le j<i \end{cases} \\ \sum\limits_{z=0}^{N_c-i}\sum\limits_{x=k-n}^{M-n-1}\sum\limits_{y=0}^{n} S(x,y,z)Q_{z,x,y} & \text{for } \begin{cases} n\le k\le M-1 \\ 0\le j<i \end{cases} \\ \sum\limits_{z=j-i}^{N_c-i}\sum\limits_{y=n-k}^{n}\sum\limits_{x=0}^{M-n-1} S(x,y,z)Q_{z,x,y} & \text{for } \begin{cases} 0\le k<n \\ i\le j\le N_c \end{cases} \\ \sum\limits_{z=j-i}^{N_c-i}\sum\limits_{x=k-n}^{M-n-1}\sum\limits_{y=0}^{n} S(x,y,z)Q_{z,x,y} & \text{for } \begin{cases} n\le k\le M-1 \\ i\le j\le N_c \end{cases} \end{cases}$$

Where $Q_{z,x,y}$ is the probability of transmitting a total of $z+i+x+y$ packets when the system is in state (i,n).Besides, following notation used in [15], $Q_{rs}(y,n)$ is the probability that y backlogged simple nodes retransmit a packet when there are n backlogged simple nodes, $Q_{as}(x,n)$ is the probability that x unbacklogged simple nodes transmit a packet and $Q_{am}(z,i)$ is the probability that the multiple node transmits z unbacklogged packets when it has i backlogged packets (unbacklogged packets in multiple node are transmitted with probability one). Following assumption 1, these probabilities are defined as follows:

$$Q_{z,x,y}=Q_{am}(z,i)\ Q_{as}(x,n)\ Q_{rs}(y,n)$$
$$Q_{rs}(y,n)=\binom{n}{y}P_r^{y}(1-P_r)^{n-y}$$
$$Q_{as}(x,n)=\binom{M-n-1}{x}P_{as}^{x}(1-P_{as})^{M-n-1-x} \tag{6}$$
$$Q_{am}(z,i)=P_{am}(z)$$

and

$$P_{as}=1-e^{-\lambda t}$$
$$P_{am}(z)=\begin{cases} \frac{(\lambda t)^z}{z!}e^{-\lambda t} & \text{for } z<N_c-i \\ 1-\sum\limits_{k=0}^{z-1}\frac{(\lambda t)^k}{k!}e^{-\lambda t} & \text{for } z=N_c-i \end{cases} \tag{7}$$

In (5), $S(x,y,z)$ determines whether it is possible to evolve from state (i,n) to state (j,k) when a total of $x+y+z+i$ packets are transmitted (remember that the i packets are transmitted with probability equal to one).Hence, $S(x,y,z)$ is defined as:

$$S(x,y,z)= \tag{8}$$
$$\sum_{t=n+x-k}^{x+y} s_{x+y,t}\frac{\binom{t}{n+x-k}\binom{i+z}{i+z-j}}{\binom{i+z+t}{n+x-k+i+z-j}}r_{t+i+z,i+z-j+n+x-k}^{M_{ll}}$$

Where:

$$s_{x+y,t}=\frac{\binom{N-N_c}{t}\ \binom{x+y}{t}\ t!\ V(N-N_c-t,x+y-t)}{(N-N_c)^{x+y}} \tag{9}$$
$$M_{ll}=M-(x+y+\delta_{z,i})$$
$$\delta_{z,i}=\begin{cases}1 \text{ if } z+i\ge 1\\ 0 \text{ Otherwise}\end{cases}$$

$s_{x+y,t}$ in (9) models the fact that codes are chosen randomly and hence, determines the probability of having t non-collided packets among the $x+y$ packets that are sent by simple nodes. A proof of $s_{x+y,t}$ is shown in the Appendix.

Since the Markov Chain defined by (5) is aperiodic and irreducible, the stationary distribution of the network state $\boldsymbol{\pi}=\left[\pi_{0,0},\pi_{0,1},\pi_{0,2},\ldots\ldots,\pi_{(N_c\times(M-1)),(N_c\times(M-1))}\right]$ can be obtained solving the balance equation:

$$\boldsymbol{\pi}=\boldsymbol{\pi}\mathbf{P} \tag{10}$$

and considering that $\sum\pi_{i,n}=1$.

IV. Throughput and Delay Optimization

The network throughput is defined as the number of packets successfully received by their intended nodes in one time slot on the average when the system is in its steady-state. Hence, given the system is in state (i,n), the expected number of packets successfully received by their intended nodes is:

$$\beta(i,n)=\sum_{z=0}^{N_c-i}\sum_{x=0}^{M-n}\sum_{y=0}^{n}Q_{z,x,y}\Big(\sum_{t=0}^{x+y}s_{x+y,t}\Big(\sum_{l=0}^{z+i+t}l\ r_{z+i+t,l}^{M_{ll}}\Big)\Big) \tag{11}$$

Hence, averaging for all the possible states and considering similarity among all users, the network throughput, depending on Nc and P_r, becomes:

$$\overline{\beta}_{N_c,P_r}=\sum_{i=0}^{N_c}\sum_{n=0}^{M-1}\beta(i,n)\ \pi_{i,n} \tag{12}$$

Besides, the system delay defined as the time on the average since the packet is generated until it is successfully received can be computed following [16]:

$$\overline{D}=\frac{\sum_{i=0}^{Nc}\sum_{n=0}^{M-1}(i+n)\ \pi_{i,n}}{\overline{\beta}_{N_c,P_r}}+R \tag{13}$$

In (13), R is referred as the deterministic delay which is the transmission delay, i.e., one slot, added to the average delay since the packet is generated until it is transmitted for the first time, i.e., half slot. Hence,

$$R=1+0.5 \tag{14}$$

It is well known that Aloha systems may present some instability[14]. However, according to [16], it is possible to properly adjust P_r in order to stabilize the system and consequently maximize the throughput and minimize the delay in the steady state. In our system, we use two parameters (P_r and N_c) to stabilize the system. For system optimization, expressions (12) and (13) must be maximized and minimized numerically:

$$\overline{\beta}_{\max} = \arg_{N_c,P_r} (\max(\overline{\beta}_{N_c,P_r})) \tag{15}$$

$$\overline{D}_{\min} = \arg_{N_c,P_r} (\min(\overline{D}_{N_c,P_r})) \tag{16}$$

V. Conclusions

In this paper a cross layer decentralized MAC protocol has been specially designed for an ad hoc network. The system is mainly an hybrid CDMA-TDMA network which by means of giving priority to different nodes at different time slots and allocating many codes to the user with priority, network resources are efficiently managed. The optimization of the system performance is based on throughput and delay numerical maximization and minimization respectively. For that purpose, a cross-layer approach has been followed and expressions for the throughput and delay of the network which explicitly depend on PHY parameters such as, the multipacket reception capability of the receiver and the number of codes Nc, have been found. The fact of handling with codes as common shared resource gives a framework to not only allocate resources more efficiently but also to possibly introducing multirate services or gain in robustness in further versions.

Appendix

We must think the factor $s_{x+y,t}$ as the probability of having t packets with one unique code when $x + y$ packets from simple nodes contend for transmission and $N - Nc$ codes were available for contention.

Lets state the following equivalent problem in order to solve $s_{x+y,t}$: We have B balls (equivalently $x + y$ packets) and N boxes (equivalently $N - Nc$ codes) and we want to know the probability $P(B, N, t)$ to have (after arranging all the balls) t and only t boxes with one and only one ball, considering that empty boxes are allowed.

To solve that problem we first choose the t boxes which will have exactly one ball (there are $\binom{N}{t}$ ways to do this). Then, we choose t balls to go into those t boxes (there are $\binom{B}{t}$ ways to do that) and choose the arrangement of those balls into these boxes (there are $t!$ ways to do that). Now, for each of those $\binom{N}{t}\binom{B}{t}t!$ choices we have to compute how many ways there are to put the remaining $B - t$ balls into the remaining $N - t$ boxes where no box contains exactly one ball.

Let $V(N, B)$ be the number of ways to arrange B balls in N boxes with no box containing exactly one ball. Given any M between 1 and N, divide the boxes into $N - M$ boxes with $B - K$ balls and M boxes with k balls. For each k, there are$\binom{B}{k}$ways to do this, so we get the recursion:

$$V(N, B) = \sum_k \binom{B}{k} V(N - M, B - k)V(m, k)$$

where $V(1, B) = 0$ if $B = 1$ and 1 otherwise. If we consider that there are a total of N^B possible combinations. The answer is then:

$$P(N, B, t) = \frac{\binom{N}{t}\binom{B}{t}t!V(N - t, B - t)}{N^B}$$

If we then, let B balls $= x+y$ codes and N boxes $= N-Nc$ codes, we finally get:

$$s_{x+y,t} = \frac{\binom{N-N_c}{t}\ \binom{x+y}{t}\ t!\ V(N - N_c - t, x + y - t)}{(N - N_c)^{x+y}}$$

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